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Wavelength-Division Demultiplexing Using Photonic Crystal Waveguides

Tapio Niemi, Lars Hagedorn Frandsen, Kristian Knak Hede, Anders Harpøth, Peter Ingo Borel, and Martin Kristensen

***Abstract*—We demonstrate a new device concept for wavelength division demultiplexing based on planar photonic crystal waveguides. The filtering of wavelength channels is realized by shifting the cutoff frequency of the fundamental photonic bandgap mode in consecutive sections of the waveguide. The shift is realized by modifying the size of the border holes. Simulations and an experimental realization of a four-channel coarse wavelength division demultiplexer are described.**

***Index Terms*—Photonic bandgap (PBG), photonic crystal (PhC) waveguide, wavelength-division multiplexing (WDM).**

I. Introduction

PHOTONIC crystal structures are considered promising building blocks for use in integrated nanophotonic circuits. Some of the most successful structures are based on planar photonic crystals (PhCs). In such waveguides, the optical field is confined, horizontally, by a photonic bandgap (PBG) provided by the PhC and, vertically, by total internal reflection due to refractive index differences. Various PhC components, such as waveguides, bends, Y splitters, and directional couplers, have already been realized [1]–[9]. These basic building blocks can be combined to realize complete circuits with various optical functions within an extremely small area.

One of the most important fields for ultra-dense integrated circuits is optical communications. A key component in modern optical communications systems is a wavelength division multiplexer (WDM). This component is needed to divide and combine different wavelength channels each carrying an optical data signal. Traditionally, WDM components are realized using thin-film filters, fiber Bragg gratings (FBG), or arrayed waveguide gratings. However, such devices are not convenient for ultra-dense integration. Various concepts for realizing a WDM component utilizing the extraordinary properties of PhCs have recently been proposed. These ideas include optical microcavities, directional couplers, multimode self-imaging waveguides, and superprisms [10]–[15].

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In this letter, we report on a novel concept for a wavelength demultiplexer. Its operation principle is based on a shift of the cutoff frequency of the fundamental PBG mode in a planar photonic crystal waveguide (PhCW). The shift is realized by varying the size of the border holes adjacent to the waveguide core. We present numerical simulations to describe the operation principle of the WDM component and show experimental results from a four-channel demultiplexer fabricated in a silicon-on-insulator (SOI) material. We believe that this device concept leads the way to a practical realization of PhC components for WDM.

II. Operation Principle

The operation principle and properties of the proposed multiplexer are described by utilizing numerical modeling in two dimensions. However, the extension of the basic principles to real three-dimensional (3-D) structures is straightforward. The PhC is defined in the top silicon (epi-) layer of an SOI material by arranging holes in a triangular arrangement. A so-called W1 PhCW is formed by removing one row of holes in the nearest neighbor direction of the PhC. The properties of the guided PhCW modes, their dispersion, and their cutoff frequencies can be obtained from the dispersion relation of the waveguide. The dispersion curves of the waveguide can be calculated by using a freely available software package, e.g., [16]. The photonic bandgap of the horizontal crystal structure supports TE-polarized waveguide modes (i.e., the magnetic field is parallel to the air holes). The fundamental PBG mode has an even symmetry with respect to center of the waveguide and the first-order mode has an odd symmetry. Usually, only the fundamental even mode is excited in the PhCW due to a large overlap with the fundamental mode of a ridge waveguide, which is often used to route light from the sample facet to the PhCW and vice versa. The propagation properties of the guided modes can be modified by altering the holes adjacent to the waveguide core. By changing the diameter of the border holes the cutoff frequency of the guided mode can be shifted either up or down in frequency [17]–[19]. Specifically, by increasing the size of the border holes the cutoff frequency can be shifted to higher frequencies.

A demonstration of how the dispersion relation of the fundamental PBG mode can be modified is shown in Fig. 1. In this example, the background material is silicon $(n = 3.476)$ and the diameter of the PhC air holes $d = 0.60\ \Lambda$ where Λ is the lattice pitch. The dispersion relation for the fundamental PBG mode is shown for diameters of the border holes D 0.60, 70, 75, 80, and 0.85 Λ.

As the diameter of the border holes is increased, the edge of the transmission band shifts to shorter wavelengths.

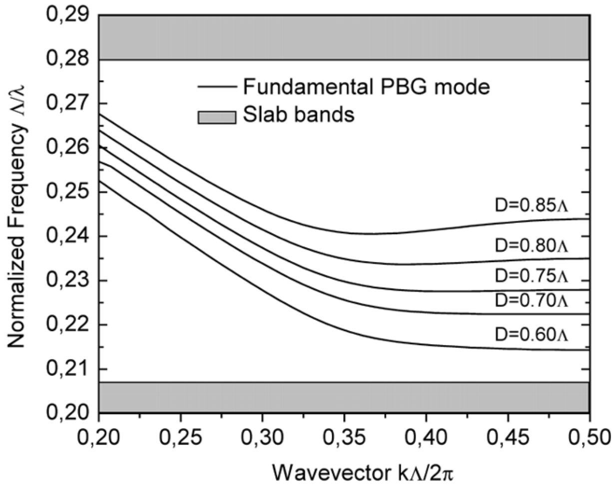

Fig. 1. Shift of cutoff frequency of fundamental photonic bandgap mode for different diameters of border holes.

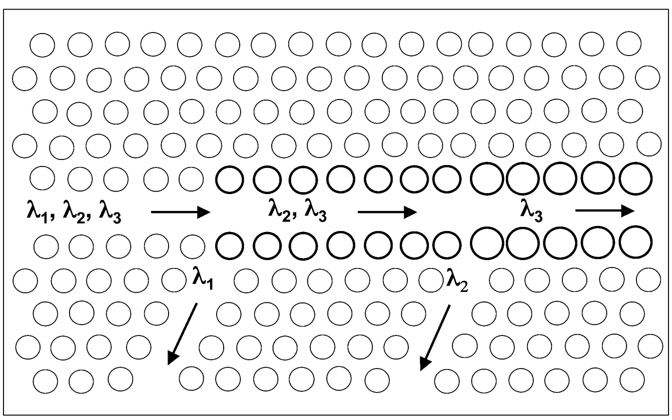

Fig. 2. Scheme of two-channel demultiplexer realized using a planar photonic crystal waveguide with consecutive sections of large border holes. With this configuration, wavelengths are demultiplexed in order $\lambda_1 > \lambda_2 > \lambda_3$.

By enlarging the size of the border holes in consecutive sections along the PhCW, this effect can be used to successively block a narrow wavelength band near the low-frequency transmission edge for being transmitted. The blocked part of the transmission band can be collected and guided in a closely and appropriately placed waveguide. In effect, a wavelength channel is demultiplexed to the adjacent PhCW from the incident signal. Therefore, a PhCW having consecutive sections with modified border holes can be applied as a multichannel optical demultiplexer. The scheme and the operation principle of a two-channel demultiplexer are displayed in Fig. 2.

III. Fabrication of Demultiplexer

We have fabricated a PhC four-channel WDM component, which experimentally verifies the demultiplexing principle described in the previous section. We use planar PhCWs defined in the top 340-nm-thick silicon layer of an SOI-wafer having a 1-μm-thick silica buffer layer. The pattern defining the PhC structures was realized in a spun-on resist by utilizing electron beam lithography. Subsequently, the pattern was transferred to the silicon layer by reactive-ion etching. The bulk PhC structure has a pitch $\Lambda = 380$ nm and the diameter of the holes is $d \approx 260$ nm. The holes are etched only through the top silicon layer. The cutoff frequency of the guided PBG mode of the waveguide was modified by changing the size of the border holes. The diameter of the holes was designed to gradually increase in steps of 20 nm between consecutive sections with lengths of 10 Λ. Four sections were fabricated having the nominal diameters of the border holes of 290, 310, 330, and 350 nm. A scanning electron micrograph (SEM) of the fabricated component is displayed in Fig. 3. The figure shows the input PhCW and the four drop channels of the component. Light is routed to the WDM component from the sample facet using a tapered ridge waveguide with a total length of ~4 mm. The ridge waveguide is tapered from 4 μm at the facets of the SOI-wafer to 1 μm at the PhCW interface. The width of 1 μm of the ridge waveguide ensures a nice overlap between the fundamental mode of the ridge waveguide and the fundamental PBG mode of the PhCW and, hence, decreases the coupling loss to the PhCW. The output of the four drop channels are connected to ridge waveguides, which are bent smoothly with a radius of ~40 μm to have their exit ports aligned parallel to the direct transmitted channel of the WDM component. This configuration simplifies the optical characterization of the component.

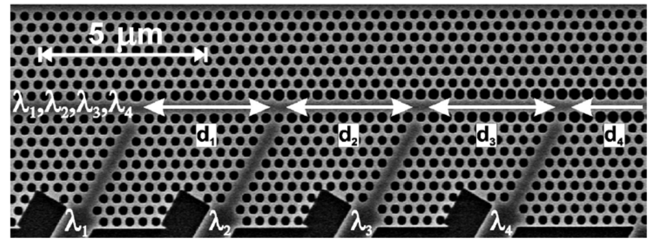

Fig. 3. SEM of fabricated four-channel demultiplexer with different border hole diameters d in consecutive sections. $d_4 > d_3 > d_2 > d_1$ and dropping of wavelengths will occur in order $\lambda_1 > \lambda_2 > \lambda_3 > \lambda_4$. Length of each of waveguide sections d_{1-4} is 10 Λ.

IV. Measurements

The components were characterized by using two broad-band light-emitting diodes (LEDs) as sources to cover the wavelength range ~1250–1550 nm. Tapered-lensed fibers were used to couple light into the ridge waveguides connected to the demultiplexer component. Two polarization controllers and a polarizer crystal were applied to obtain the TE-polarization of the waveguides. The output from each of the channels was recorded with an optical spectrum analyzer using a resolution bandwidth of 10 nm. The recorded spectra were normalized to the transmission of a tapered ridge waveguide with a length of ~4 mm. The measured spectra for each of the demultiplexed channels are displayed in Fig. 4. The different drop channels peak around 1345, 1385, 1405, and 1440 nm for the channels $\lambda_1, \lambda_2, \lambda_3$, and λ_4, respectively. The difference in transmission level between the channels is primarily due to propagation losses in the PhCW sections.

V. Discussion

We have proposed a novel device concept for an integrated optical demultiplexer based on planar photonic crystal structures. Measured spectra on a fabricated component show an ex-

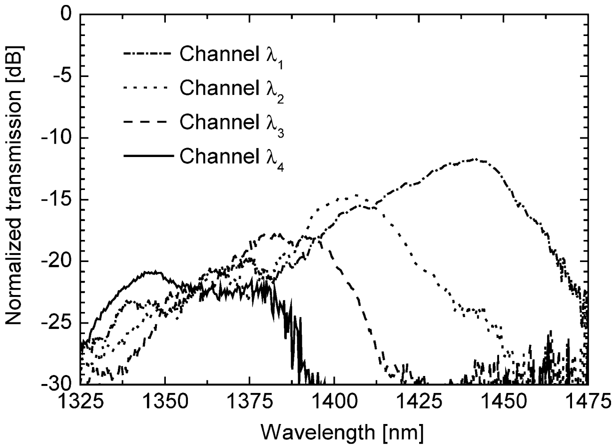

Fig. 4. Demultiplexed wavelength channels from fabricated component. Spectra have been normalized to transmission through tapered ridge waveguide.

perimental verification of the operational principle. However, the width of each dropped wavelength channel, loss, crosstalk, and the varying channel spacing calls for further improvement and optimization before this component can be utilized in practical applications. The loss of the component is most likely a result of coupling to the silica layer since the operation range of the waveguides is close to the light line. Some additional loss may be due to coupling of TE-like modes to TM-like slab modes resulting from the asymmetric SOI structure [20], [21].

The operation of the component is based on shifting the long-wavelength edge of the transmission band of the TE-like even mode of the waveguide. The shift of the edge is very sensitive to perturbations of the border holes adjacent to the waveguide core. The wavelength shift related to the diameter of the border holes is $\sim$2 nm/nm in our device. Wavelengths falling outside the transmission band cannot propagate in the waveguide but form an evanescent wave. Hence, the main part of the light is reflected back. The key issue in the operation of the proposed demultiplexer is to collect the signal to the drop channels. In the present configuration, the intersections between two waveguides with different border hole diameters were slightly optimized by applying a large hole opposite to the drop channel (see Fig. 3). However, further modeling is needed to understand and optimize the complex coupling mechanism, which also includes evanescent waves and resonance effects. One promising method for designing optimized photonic crystal structures in a systematic way is topology optimization [5], which could be utilized to improve the general characteristics of the component.

In conclusion, we have demonstrated a novel component for wavelength demultiplexing based on photonic crystal waveguides. This device leads the way to achieve the CWDM channel spacing of 20 nm defined by ITU-T Recommendation G.694.2. We believe that this component is one of the first experimental demonstrations of doing in-plane multichannel filtering and demultiplexing.

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